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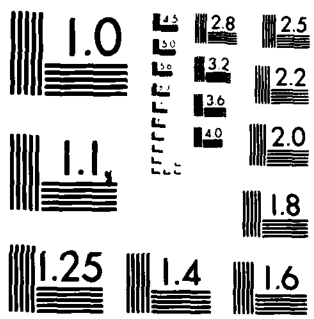

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CLOSED ENERGY CYCLE WITH MHD GENERATOR USING T-LAYER EFFECT

by

V.S. Slavin, V.S. Sokolov

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
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К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
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М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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CLOSED ENERGY CYCLE WITH MHD GENERATOR USING T-LAYER EFFECT

V. S. Slavin, V. S. Sokolov

I. We are aware of the many proposals (for example, [1, 2]) on the use of so-called stratified flows for the purpose of increasing the efficiency of energy conversion in MHD generators. Characteristic of most of these proposals is, first, an attempt to increase the average value of electrical conductivity in the working body by creating temperature heterogeneities or a concentration of the additives in the flow and, second, the artificial nature of these heterogeneities, which reduces the problem of using stratified flows to problems of obtaining these heterogeneities and then making them stable.

Described in [3] is the phenomenon of a developing T-layer in a gas flow from a certain initial disturbance or the presence of an external magnetic field. The condition for development ("capture") of the disturbance is the inequality

$$\frac{4\pi}{C^2}\sigma_0 U_0 L_0 \frac{H_0^2}{8\pi P_0} > \text{const}, \qquad (1)$$

i.e., if the local disturbance in temperature or electrical conductivity is such that electrical conductivity σ_0, velocity U_0, linear dimension L_0, pressure P_0, and magnetic field H_0 satisfy this inequality, then a T-layer will develop from the disturbance. Otherwise the disturbance will be damped. The value of the constant in the right side of the

inequality is determined by the geometry of the channel and the nature of the stream.

A flow with a T-layer represents one case of the stratified flows mentioned above, although it does have two basic distinguishing features. First, the T-layer develops spontaneously and is self-sustained. Thus the problem of the stability of the stratified structure acquires a different meaning. From this property of spontaneous development of the T-layer it follows that, in comparison to other types of stratified flows, the flow with the T-layer for the creation of modulation should require less energy from external sources. The magnitude of this requirement is determined only by the requirement for creating the initial disturbance, while the T-layer thereafter develops by the energy of the "cold" gas through joule dissipation. In addition, the presence of a high-temperature T-layer in the flow enables a spatial separation of functions of the working fluid, i.e., the role of the electrical conductor is played not by the entire volume of the gas, but rather by the small portion of it found in the T-layer. The remaining gas simply becomes a working fluid, whose entropy is subject to conversion into electrical energy. In a certain sense this separation is inherent in all types of stratified flows, although in the case of the T-layer the separation is absolute.

In this article we examine the theoretical possibility of using a MHD generator with a T-layer in closed energy cycles. The presence of the T-layer in the gas stream assures that the flow will interact quite effectively with the magnetic field, which in turn enables us to calculate the possibility of creating an induction MHD generator. However, in view of the fact that the thermodynamic nature of the process within the generator is independent of the type of MHD generator, in this study we have made no distinction between conduction and induction systems. As our working fluid we examine an inert gas with an alkali metal additive.

II. The basic scheme of the generator with the T-layer can be described as follows. At the inlet to the MHD channel a temperature irregularity is created in the flow of the working fluid at a certain frequency. From this the T-layer develops. The thermodynamics of this process, with a number of simplifications, are shown schematically in Fig. 1. Corresponding to point 0 are the parameters of the gas at the reactor output. The dashed line represents the proposed process for heating of the T-layer, which is replaced by two ideal processes. Here it is assumed that the T-layer at the channel input is already formed and that point 1 determines the average parameters of the flow at the input. Point 3 corresponds to the parameters of the working fluid at the MHD generator output after the flow has once again become uniform. Analysis is based on the following assumptions:

1. The gas in "hot" layer is preheated in an isobaric process and then expands isothermically in the generator channel.

2. The cold layers are not electrically conductive and react with the magnetic field only through the hot gas. The cold gas expands isoentropically.

3. In the channel layers with different temperatures do not mix and retain their part by mass during the entire working process (the part by mass of the T-layer is designated as α).

4. The working body is subject to the equation of state of an ideal gas.

These proposals make it possible to determine the internal adiabatic efficiency of a generator as

$$\eta_{oir} = \frac{T_1 - T_2}{T_1 - T_2'}. \qquad (2)$$

Using thermodynamic relationships, (2) can be rewritten as

$$\eta_{oir} = \frac{\alpha}{\alpha + (1-\alpha) T^{*}_{\text{Т-сл}}}, \qquad (3)$$

where $T^{*}_{\text{т-сл}} = T_{\text{т-сл}}\, T_0$ is the relative temperature of th T-layer. An essential thermodynamic characteristic of the stream with the T-layer is the necessary increase in average stream enthalpy for the formation of the initial temperature disturbance in it. Within the framework of these assumptions, this magnitude equals

$$\Delta_i = C_p\, T_0 (1-\alpha)(T^{*}_{\text{т-сл}} - 1). \qquad (4)$$

III. For thermodynamic analysis let us use a cycle whose efficiency has been established in many studies [4]. The heating and cooling of the working fluid is achieved in the isobaric processes. In the generator the gas expands adiabatically. Compression occurs in a three-stage compressor with intermediate cooling. Two systems can be employed to use the heat of the gases discharged from the generator: a system with a regenerative heat exchanger and a system with a steam turbine cycle. It is also possible to use a combination cycle [4] in the creation of the studied MHD generator.

In the thermodynamic analysis let us ignore losses to friction in the reactor and heat exchanger and heat losses through the walls of the assemblies.

The basic scheme with regenerative heat exchanger is shown in Fig. 2a. In Fig. 2b we see the cycle in T-S coordinates. The efficiency of this cycle is determined as

$$\eta_e = \frac{C_p (T_1 - T_2')\,\eta_{0ir} - 3C_p (T_5' - T_4)(\eta_{0i\kappa} - C_p (T_1 - T_0)}{C_p (T_0 - T_{10})}. \qquad (5)$$

Now, using the relationships for the ideal processes which constitute this cycle, it is possible to rewrite (5) in the following form:

$$\eta_e = \frac{\left(\frac{\Delta i}{C_p T_0} + 1\right)\left(1 - \beta^{-\frac{\varkappa-1}{\varkappa}}\right)\eta_{0ir} - 3T_4^{*}\left(\beta^{\frac{\varkappa-1}{3\varkappa}} - 1\right)\Big|\eta_{0i\kappa} - \frac{\Delta i}{C_p T_0}}{1 - \left(\frac{\Delta i}{C_p T_0} + 1\right)\left[1 - \left(1 - \beta^{-\frac{\varkappa-1}{\varkappa}}\right)\eta_{0ir}\right] + \Delta T^{*}}. \qquad (6)$$

where $\frac{\Delta i}{C_p T_0}$ is the relative increase in average temperature in the flow after creation of the initial disturbance; $\Delta T^* = (T_2 - T_{10})/T_0$ is the temperature head in the heat exchanger; β - the degree of compression in the compressor; $T_4^* = T_4/T_0$ - relative temperature of the surrounding medium; η_{0ir} - internal adiabatic efficiency of generator; $\eta_{0iк}$ - adiabatic efficiency of compressor.

As already observed, the binary cycle is distinguished from the first system by its method of utilizing residual heat. In this case it is not necessary to use a three-stage compressor and compression can be achieved in one adiabatic process. In the steam turbine portion of the cycle we assume that it is capable of converting 40% of the heat yielded in the steam generator into electrical energy. In Figs. 3a and b we see a schematic representation of this cycle and the T-S diagram.

By analogy with the first type we can obtain the efficiency relationship for the binary cycle in the form of:

$$\eta_e = \left\{\left(\frac{\Delta i}{C_p T_0} + 1\right)\left[\left(1 - \beta^{-\frac{\varkappa-1}{\varkappa}}\right)_{\eta_{0ir}} \cdot 0{,}6 + 0{,}4\right] - \right.$$
$$\left. - T_4^*\left(\beta^{\frac{\varkappa-1}{\varkappa}} - 1\right) \Big/ \eta_{0iк} - \frac{\Delta i}{C_p T_0} - 0{,}4 T_3^*\right\} \Big/ 1 - T_4^*\left[1 + \left(\beta^{\frac{\varkappa-1}{\varkappa}} - 1\right) \Big/ \eta_{0iк}\right], \qquad (7)$$

where $T_3^* = T_3/T_0$ is the temperature of the gas after cooling in the steam generator.

Now let us determine the value of the constants. Temperature T_4 is determined by the conditions of the environment. Let us select a temperature value which is equal to 300°K and a value of $\eta_{0iк}$ of 0.85. In keeping with [4] we select reactor working temperatures of: 2000, 2300, and 2600°K. The value of T_3 in the binary cycle is assumed to be equal to 500°K. The values of η_{0ir} and $\Delta i/C_p T_0$ are determined by the parameters of the T-layer.

Figures 4-8 show the dependence of the efficiency of the cycles on β: T_0; ΔT, α; $T_{\text{т-сл}}$.

IV. The results obtained from the calculation show that the efficiency of the MHD generator with a stratified flow can be essentially determined by the parameters of the hot regions in the flow and the initial temperature of the "cold" layers. The limit values of these parameters can be indicated. Thus, for example, the fraction of hot layers in the mass of the entire flow should not exceed 10%, while the temperature of the gas at the reactor output should be greater than 2300°K. With all remaining parameters constant the increase in the temperature of the T-layer leads to a decrease in total efficiency. However, this temperature is not a free parameter; rather it is determined by the specific generator process. A comparison with the binary cycle shows us that until a level of 2300°K is attained in reactor technology, the cycle which uses the steam turbine will be more effective than a purely regenerative cycle. If we compare the obtained results with [4], then we see that the maximal efficiency values of closed cycle with MHD generators which employ nonequilibrium conductivity and a T-layer virtually coincide.

V. Now let us present some estimates for the specific values of cycle parameters, particularly pressure at the input of the MHD channel, magnetic induction, and the temperature of T-layer. Our estimates are based on inequality (1). Let us assume that the conditions for the flow in the MHD channel are such that the value of the constant and the right side of inequality (1) equals 0.5 [3]. Let us also assume that the characteristic velocity of the flow U_0 = 1000 m/s and that the width of the disturbance zone is 0.5 m (for a channel several meters long this value is quite suitable). If B_0 = 5 T, while the pressure at the channel input is 50 atm, then from (1) it follows that $\sigma \geqslant$ 400 mho/m.

To achieve the T-layer effect it is necessary that the conductance of the gas rise as temperature rises. In a mixture of inert gas with alkali metal vapors, where only the atoms of the additive are ionized, electron-ion interactions must prevail in order to satisfy this

condition. Under these conditions conductivity is determined by the partial pressure of the alkali metal vapors. If the additive is cesium (~ 2%), then a conductivity of 400 mho/m is achieved at a temperature of 3200°K [5]. The M number of the flow at the input to the generator channel is $\gtrsim 1$, pressure in the reactor in this case ~100 atm. Consequently, in view of the equilibrium nature of conductivity in the T-layer, pressure in a generator with a stratified flow can be significantly increased and is determined by the conditions of optimal work of the nuclear reactor.

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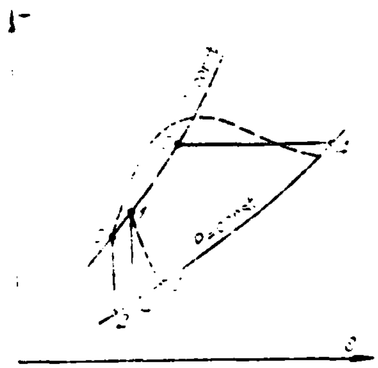

Fig. 1.

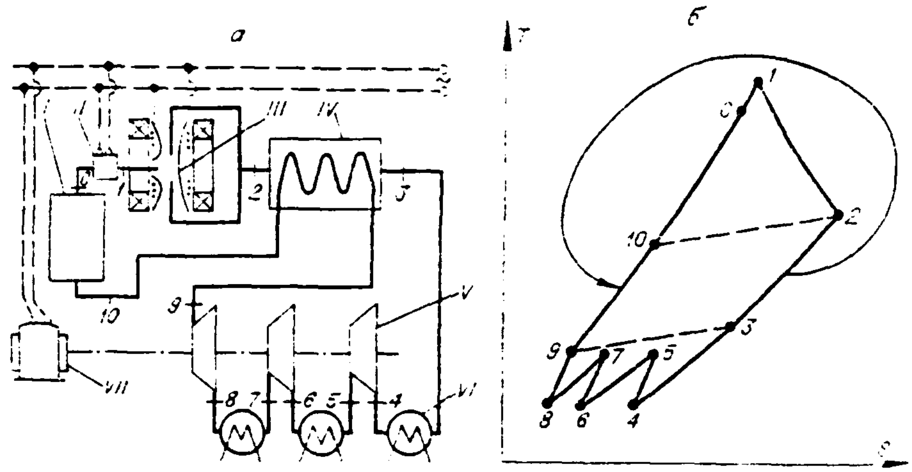

Fig. 2. I - Reactor; II - Device which creates initial temperature disturbance; III - MHD generator; IV - Regenerative heat exchanger; V - Compressor; VI - Water heat exchanger; VII - Electric motor.

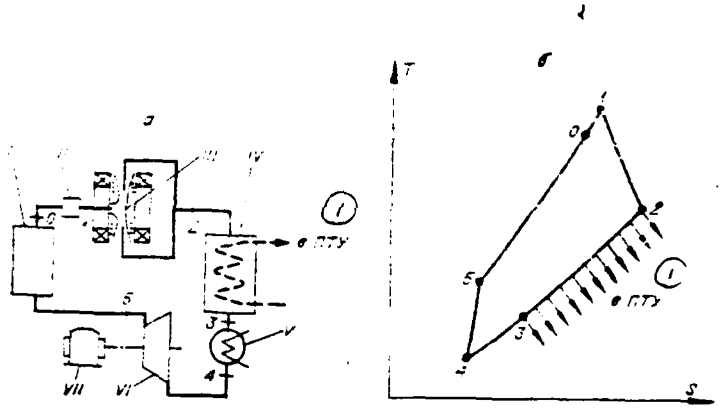

Fig. 3. I - Reactor; II - Device which creates initial temperature disturbance; III - MHD generators; IV - Steam generator; V - Water heat exchanger; VI - Compressor; VII - Electric motor.

KEY: (1) to steam turbine.

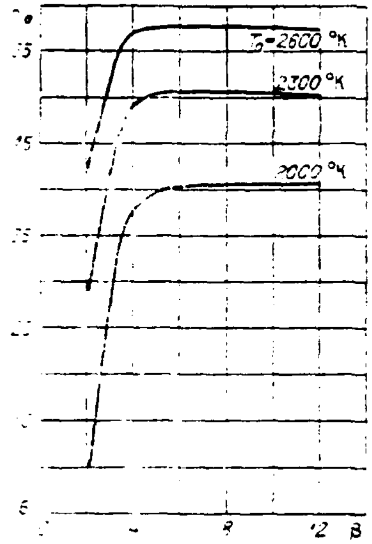

Fig. 4.

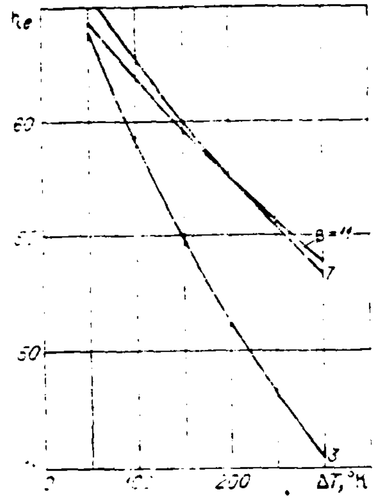

Fig. 5.

Fig. 4. Efficiency of cycle with total regeneration. Cycle parameters: T_0 = 2000, 2300, 2600°K, ΔT = 200°K. Parameters of T-layer: $T_{T\text{-сл}}$ = 5000° K, α=0.9.

Fig. 5. Efficiency of cycle with total regeneration as function of temperature drop in regenerative heat exchanger. Cycle parameters: T = 2600° K, β=3; 7; 11 Parameters of T-layer: $T_{T\text{-сл}}$=5000° K α=0.9

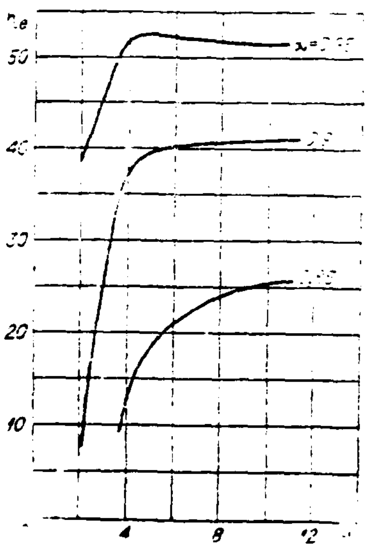

Fig. 6.

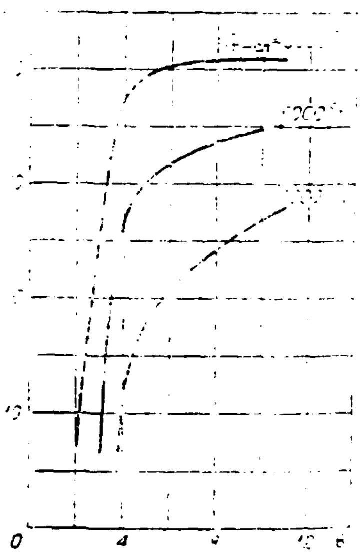

Fig. 7.

Fig. 6. Efficiency of cycle with total regeneration. Cycle parameters: T_0 = 2000°K, ΔT = 200°K. Parameters of $T_{T\text{-сл}}$ = 5000° K, α=0.85; 0.9; 0.95.

Fig. 7. Efficiency of cycle with total regeneration. Cycle parameters: T_0 = 2000°K, ΔT = 200°K. Parameters of T-layer: $T_{T\text{-сл}}$=5000, 6000, 7000° K, α=0.9.

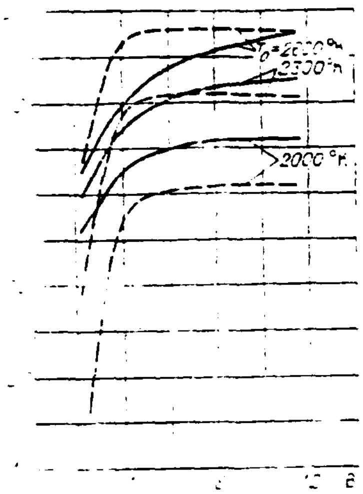

Fig. 8. Efficiency of binary cycle. Analogous curves are presented for cycle with regeneration (dash line) for comparison. Cycle parameters: T_0 = 2000, 2300, 2600°K; ΔT = 200°K. Parameters of T-layer: $T_{T\text{-}сл}$ [illegible]

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